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Ship Acoustics Department

Departmental Report

Effects of Frequency, Temporal, and Spatial Averaging on Image Interference

by

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ABSTRACT

This report describes a significant phenomenon affecting the propagation of underwater sound at ranges less than 1000 yards: the image interference or Lloyd-mirror effect. Previous models for the effect do not adequately take into account the effects of frequency averaging and spatial averaging due to sea surface roughness and finite source size. These refinements on the basic theory are developed here. Also a clarification of the meaning of the surface reflection coefficient is given for the case of omnidirectional sources and receivers -- the situation that prevails in ship radiated-noise trials.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The reflection and scattering of underwater sound from the ocean surface is a phenomenon that has been studied extensively since the time of Rayleigh (1). In fact, the approach taken by Rayleigh has been followed by many investigators up to the present time. Most of the theoretical literature deals with the Rayleigh problem: a plane wave insonifying a small area on the sea surface. Reports on experiments often deal with an approximation to this; that is, a narrow-beam transmitter and receiver aimed at a small area on the sea surface or some model of the surface.

The situation of interest in ship acoustical trials is best represented by an omnidirectional source and receiver under a moderately rough sea surface. The received signal is time-averaged for a duration that is long compared with the sea surface fluctuations. This is a limiting case that is not directly reported in the literature; however it is relatively easy to devise an adequate expression to account for this case. Only the time-averaged rms pressure is needed; there is no need for consideration of coherent and incoherent scattering, or the statistics of the time-varying surface.

This report proposes simple equations for the time-average rms received pressure from an omnidirectional source in the vicinity of the sea surface.

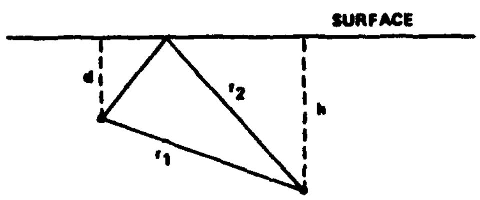

Figure 1 - Geometry of the image interference effect

At low frequencies where absorption is not significant, and neglecting refraction effects, the mean-square pressure at a receiver in the vicinity of a flat pressure-release surface can be written

$$\langle p^2 \rangle_t = \frac{P_o^2 r_o^2}{r_1^2} \left[1 + \frac{\mu^2 r_1^2}{r_2^2} - \frac{2\mu r_1}{r_2} \cos 2\pi f_o T \right]$$

where r_1 and r_2 are ray distances as shown in Figure 1; f_o is the signal frequency; $T = \frac{r_2 - r_1}{c}$ = the time difference in arrivals via r_1 and r_2; μ is the surface reflection loss coefficient (can vary from 0 to 1). (In the general case where the sound speed c is not a constant, refraction will be present, so r_1 and r_2 will not be straight lines.) For the sake of simplicity, let the reference pressure $P_0 = 1$ and $r_0 = 1$.

AVERAGE OVER A FREQUENCY BAND

It can be shown (Appendix A) that, for a band of frequencies of bandwidth B and arithmetic center frequency f_0, the mean-square received pressure may be written as

$$\langle p^2 \rangle_t = \frac{P_o^2 r_0^2}{r_1^2} \left[1 + \frac{\mu^2 r_1^2}{r_2^2} - \frac{2\mu r_1}{r_2} \frac{\sin \pi B T}{\pi B T} \cos 2\pi f_o T \right] \qquad (2)$$

where the factor $\rho = \frac{\sin \pi B T}{\pi B T}$ may be interpreted as a dimensionless cross-correlation coefficient (with time delay T), between the sound pressures from the direct and surface-reflected paths. This equation only can apply when the sea surface is smooth enough so that the ocean wave height is small compared to acoustic wavelength, or when the surface scattering is small. If this is not the case, a more general expression must be obtained that takes account of the sea roughness as well as bandwidth.

EFFECT OF ROUGH SEA SURFACE

The following five points constitute a heuristic argument to arrive at a more general theory for the omnidirectional transmission loss as a function of both bandwidth and sea surface roughness (wave height).

1. Most of the discussions of surface loss (2) in the literature apply to narrow-beam sources and/or receivers. Actually the value of μ referred to in this case is a partitioning factor indicating the relative amount of sound energy that is scattered out of the specular direction, that is, the ratio of specularly-reflected pressure to the total incident pressure. The justification for this interpretation of μ is that there is very little actual energy loss due to reflection of sound from the sea surface. The available mechanisms for such real dissipative surface loss are, in general:

   a) Transmission through the surface: causes a very small reflection loss of .005 dB

   b) Absorption by bubbles: also estimated at about .005 dB below 10 kHz

   c) Absorption by organisms: varies, but generally very small.

At high frequencies, (say 50 kHz) the loss due to bubbles may become significant at low grazing angles where the sound travels through an extensive thickness of bubbles. Therefore, with this exclusion, we can let $\mu = 1$ and remove it from equations 1 and 2.

2. Since ship noise measurements are almost always time-averaged measurements, it is not necessary to treat coherent and incoherent reflected sound separately, as is often done in the literature (2). Equation (2) is expressed in a convenient form such that there can be one correlation factor, g, which will com-

pletely describe the effect of the surface on reflected sound, for any degree of surface roughness.

3. Equation (2) describes a form of the image-interference effect as a function of bandwidth B which has the following properties:

a) For B=0, equation (2) reduces to equation 1, which is the case of image interference from a flat surface.

b) For $B \gg 2f_0$, equation (2) reduces to the limiting case of wideband noise:

$$p^2 = \frac{p_o^2 r_o^2}{r_1^2} \left[1 + \frac{r_1^2}{r_2^2} \right] = \left[\frac{1}{r_1^2} + \frac{1}{r_2^2} \right] p_o^2 r_o^2 \qquad (3)$$

which is purely a function of geometry. This function is shown in Figure 2. The ordinate in this figure is plotted in terms of the increase in pressure level (in dB) due to the presence of the surface path. The 0-dB line represents the free-field transmission loss 20 log r_1. The abscissa is plotted in terms of the dimensionless geometry parameter $\sqrt{\frac{dh}{r_1}}$. (The levels given are strictly applicable only to the case of isovelocity water.) Notice however, that the maximum contribution from the surface path is only 3 dB. This indicates why exact theoretical derivations (such as by integrating the results for narrow-beam theory) are unnecessary and a simple definition of correlation is sufficient. Measurement precision and omnidirectionality of real transducers rarely are better than 1 dB.

4. The dimensionless surface roughness parameter commonly applied is the Rayleigh parameter

$$R = k\,\sigma \sin\alpha = 2\pi \frac{\sigma}{\lambda_o} \sin\alpha = \frac{2\pi f_o \sigma}{c} \sin\alpha$$

where σ is the rms wave height, α is the grazing angle of the specular ray, and

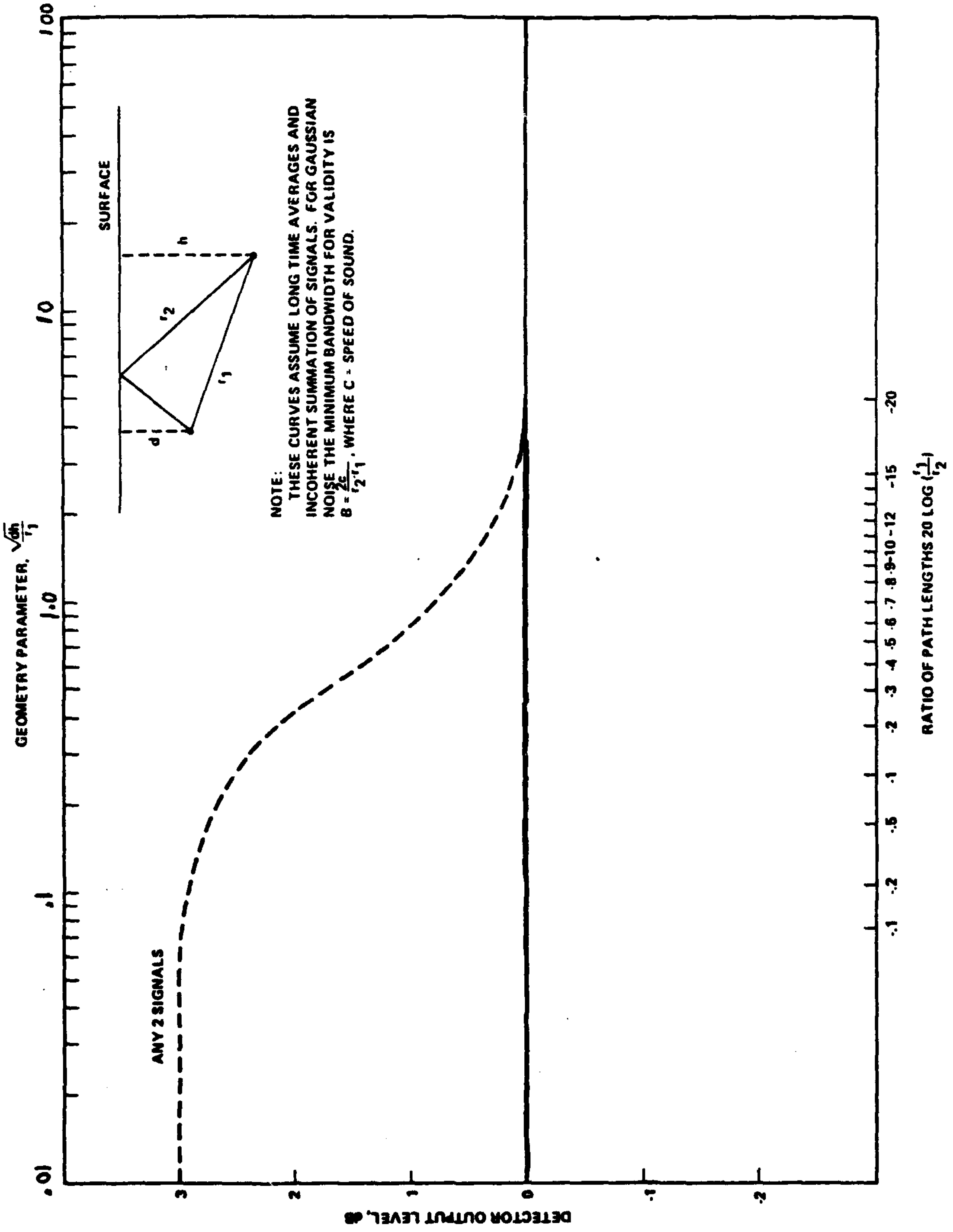

Figure 2. Increase in mean level of wideband noise signals due to surface reflected sound as a function of geometry (square-law detector assumed).

λ_0 is the wavelength of sound of frequency f_0. In the case of scattering from a narrow beam of sound, α has a unique value. This is the case usually treated in the literature. However, in the case of an omnidirectional source, sound is scattered at all angles from a rough surface. Nevertheless, we can retain the specular-reflection value for α in the latter case. The justification for this is that α is always the angle from which most of the sound will be reflected on a time-average basis, and angles within, say, 10 percent of α will usually cover a large portion of the scattered sound pressure (3). Therefore the Rayleigh parameter will be retained with the above extension of its definition implied in the case of an omnidirectional source.

If the sea surface is flat, equation (2) applies, for any band of frequencies centered at f_0. But if we assume a very rough surface, such that $R > 10$, it is clear that the reflected ray will be uncorrelated with respect to the direct ray, regardless of the value of B. In other words, even with $B=0$, equation (3) will apply when R is large.

5. Both B and R affect the correlation factor. It seems likely that they both affect it to the same degree, because both are dimensionless ratios of lengths, the limiting values are the same, and they are both conservative: they only affect the received phase; there is no amplitude loss. From the above considerations we infer a combined expression for the correlation factor of the form:

$$g = \frac{\sin(\pi BT + R)}{\pi BT + R} . \tag{4}$$

It is clear that the effects of B and R are additive, because when one term is small and the other large, the large one dominates. It also seems reasonable that both B and R have equal weight in determining the correlation factor, g.

Therefore a general expression for the received mean square sound pressure from an omnidirectional point source and receiver under a rough sea surface may be written

$$\langle p^2 \rangle_t = \frac{p_o^2 r_o^2}{r_1^2} \left[1 + \frac{r_1^2}{r_2^2} - \frac{2r_1}{r_2} \frac{\sin(\pi BT+R)}{\pi BT+R} \cos 2\pi f_o T \right] \quad (5)$$

AVERAGE OVER A FINITE-SIZE SOURCE

Equation (5) may be extended further to include the effect of spatial averaging in a vertical dimension caused by a source of finite size. This situation occurs, for instance, in the case of a cavitating propeller on a surface ship, where the collapsing cavitation bubble is extended in depth and radiates sound across this extended region.

In this case the depth-averaging term has a form that is identical to the Rayleigh parameter, except that the rms wave height s is replaced by the rms vertical source width d:

$$Z = 2\pi \frac{d}{\lambda} \sin \alpha = \frac{2\pi d}{c} f_0 \sin \alpha$$

This is the correlation factor for spatial averaging in the vertical dimension. Clearly this factor is additive with the other factors. Therefore, the resultant image interference equation is obtained by adding all three factors:

$$g = \frac{\sin(\pi BT + R + Z)}{\pi BT + R + Z}$$

so that the resulting image interference equation becomes

$$\langle p^2 \rangle_t = \frac{p_o^2 r_o^2}{r^2} \left[1 + \frac{r_1^2}{r_2^2} - \frac{2r_1}{r_2} \frac{\sin (\pi BT+R+Z)}{\pi BT+R+Z} \cos 2\pi f_o T \right] \qquad (6)$$

This model of the image interference anomaly has been implemented in a BASIC-language program for the Hewlett-Packard 9845 computer. A listing is included in Appendix B. The program uses conventional 1/3-octave frequency bands and can accept up to 4 receiver depths in a vertical array, with two commonly-used methods of averaging the data from different receivers.

Appendix A. Derivation of Image Interference Term for a Band of Frequencies

Equation (1) applies only to the case of a single frequency f_o, whereas it is more usual to measure noise in a band of frequencies $B = f_2 - f_1$. In this case the third term in equation (1) must be averaged over frequency:

$$I = \frac{1}{2\pi BT} \int_{f_1}^{f_2} \cos 2\pi f T \, df.$$

Defining $f_o = \frac{f_1+f_2}{2}$, $\theta_1 = \pi f_1 T$ and $\theta_2 = \pi f_2 T$, we obtain

$$I = \frac{1}{2\pi BT} \left[\sin 2\pi f_2 T - \sin 2\pi f_1 T\right]$$

$$= \frac{1}{2\pi T(f_2-f_1)} \left[\sin 2\pi f_2 T - \sin 2\pi f_1 T\right]$$

$$= \frac{1}{2(\theta_2-\theta_1)} \left[\sin 2\theta_2 - \sin 2\theta_1\right]$$

$$= \frac{1}{\theta_2-\theta_1} \left[\frac{\sin 2\theta_2}{2} - \frac{\sin 2\theta_1}{2}\right]$$

$$= \frac{1}{\theta_2-\theta_1} \left[\sin \theta_2 \cos\theta_2 - \sin\theta_1 \cos\theta_1\right]$$

$$= \frac{1}{\theta_2-\theta_1}\left[(\cos^2\theta_1 + \sin^2\theta_1) \sin\theta_2 \cos\theta_2 - (\sin^2\theta_2 + \cos^2\theta_2) \sin\theta_1 \cos\theta_1\right]$$

$$= \frac{1}{\theta_2-\theta_1}\left[\sin \theta_2 \cos^2 \theta_1 \cos \theta_2 - \sin^2 \theta_2 \cos \theta_1 \sin \theta_1 - \cos^2 \theta_2 \sin \theta_1 \cos \theta_2\right.$$

$$\left. + \cos \theta_2 \sin^2 \theta_1 \sin \theta_2\right]$$

$$= \frac{\sin \theta_2 \cos \theta_1 - \cos \theta_2 \sin \theta_1}{\theta_2-\theta_1} \left[\cos \theta_1 \cos \theta_2 - \sin \theta_1 \sin \theta_2\right]$$

$$= \frac{\sin(\theta_2 - \theta_1)}{\theta_2 - \theta_1} \cos(\theta_1 + \theta_2)$$

$$= \frac{\sin \pi BT}{\pi BT} \cos 2\pi f_o T.$$

```
10    ! LLOYDD        LLOYD-MIRROR INTERFERENCE FOR 1/3-OCTAVE MEASUREMENTS
20    ! PAUL ARVESON            REVISED JUNE 2, 1983
30    ! DATA STORAGE VERSION OF LLOYDP
40    ! BASED ON FORTRAN PROGRAMS BICENT (CCPAP), PSM (CCPAM), AND OTHER WORK
50    !    This program generates anomaly in propagation loss due to surface
60    ! image interference as well as anomalies due to hydrophone direction-
70    ! ality, absorption loss, and detector type.  Options are available
80    ! to account for averaging due to a vertical source width
90    ! and hydrophone averaging method (average of dB levels or average of
100   ! powers before dB conversion).
110   !    The program does not account for sometimes significant effects
120   ! due to averaging over range during sample time, refractive anomalies,
130   ! or bottom reflections.
140   OPTION BASE 1
150   PRINTER IS 16
160   GCLEAR
170   PRINT PAGE
180   DIM D2(10),Freq(41),P(10),Asum(41),Dbsum(41),Db(10,41)
190   DIM Fre(41),A(10,41),Akyds(21),X(41),Y(41),P$(6),C$[80]
200   SHORT Xsum(34)
210   DATA .0053,.0068,.0085,.104,.13,.164,.215,.293,.415,.604,.9,1.36,2.07
220   DATA 3.14,4.73,7,10.1,14.1,18.8,23.9,29
230   MAT READ Akyds
240   RESTORE 210
250   Fmax=34          !   UPPER FREQUENCY IS 20,000 Hz
260   Msus1$=":"
270   Det=1
280   PRINT "PROPAGATION ANOMALY DATA"
290   BEEP
300   INPUT "SQUARE LAW DETECTORS ARE ASSUMED; IF LINEAR ENTER 1",L$
310   IF L$="1" THEN Det=PI/4
320   BEEP
330   INPUT "ENTER LENGTH OF HYDROPHONE ELEMENT IN INCHES",Hyl
340   Hyd=Hyl/12
350   BEEP
360   INPUT "ENTER OCEAN WAVE HEIGHT IN FEET",Wh
370   BEEP
380   INPUT "ENTER MEAN SOURCE DEPTH IN FEET",D1
390   BEEP
400   INPUT "ENTER SOURCE VERTICAL WIDTH IN FEET",Dx
410   IF D1>=Dx THEN GOTO 460
420   BEEP
430   DISP "ERROR -- SOURCE NOT FULLY SUBMERGED"
440   WAIT 1500
450   GOTO 370
460   BEEP
470   INPUT "ENTER HORIZONTAL RANGE IN YARDS",Cpay
480   BEEP
490   INPUT "HOW MANY HYDROPHONES ARE AVAILABLE?",Nhyd
500   IF Nhyd<>0 THEN GOTO 550
510   BEEP
520   DISP "BAD INPUT, TRY AGAIN"
530   GOTO 480
540   MAT D2=(0)
550   FOR I=1 TO Nhyd
560    BEEP
570    INPUT "ENTER DEPTH OF HYDROPHONE IN FEET",D2(I)
580   NEXT I
590   !  START OF COMPUTATIONS - - - - - - - - - - - - - - - - - - - - - - - -
600   Cpa=3*Cpay
610   Cpaq=Cpa^2
620   C=5000          !  Sound speed in feet per second
630   Avg1=1
640   Avg2=0
650   DISP "WAIT A MINUTE -- I'M THINKING"
660   FOR I=1 TO Nhyd  ! - - - - - - - HYDROPHONE DEPTH LOOP  - - - - -
```

```
670   Sum=D1+D2(I)
680   Diff=D1-D2(I)
690   Rsq=Cpaq+Diff^2
700   Rrsq=Cpaq+Sum^2
710   R=SQR(Rsq)              !     Source to hyd. distance
720   Rr=SQR(Rrsq)            !     Image to hyd. distance
730   P(I)=SQR(D1*D2(I))/R   !   Geometry parameter for surface reflections
740   Theta1=PI/2
750   Theta2=PI/2
760   RAD
770   IF Cpa>0 THEN Theta1=ATN(Diff/Cpa)   !  Angle source to hyd.
780   IF Cpa>0 THEN Theta2=ATN(Sum/Cpa)    !  Angle image to hyd.
790   Angle(I)=ABS(Theta1*180/PI)
800   W=R/Rr
810   T=(Rr-R)/C
820    FOR F=1 TO Fmax !- - - - - - - - - - -   FREQUENCY LOOP - - - - - - - - -
830    Freq=10*10^(.1*(F-1))
840    Fre(F)=DROUND(Freq,3)
850    E1=E2=1                 !  Absorption loss negligible below 1 KHz.
860    Lambda=C/Freq
870    IF F<21 THEN GOTO 910
880    Alpha=Akyds(F-20)/60000  !  Divide by 3000*20 to give exp. loss per foot
890    E1=10^(-Alpha*R)        !  Absorption loss factor for R
900    E2=10^(-Alpha*Rr)       !  Absorption loss factor for Rr
910    Dir1=FNDirect(Theta1,Lambda,Hyd)
920    Dir2=FNDirect(Theta2,Lambda,Hyd)
930    C1=E1*Dir1
940    C2=E2*Dir2
950    Sina=Sum/R              !  Sine of angle from image to hyd.
960    B=.2316*Freq            !  Bandwidth in hertz
970    Z1=PI*B*T               !  Bandwidth integral
980    Z2=2*PI*Dx*Sina/Lambda!  Integral over source width  (NEW VERSION)
990    Z3=2*PI*Wh*Sina/Lambda!  Integral due to surface roughness (Rayleigh)
1000   X=Z1+Z2+Z3
1010   Corr=SIN(X)/X
1020   A(I,F)=C1^2+(W*C2)^2-2*W*C1*C2*Corr*COS(2*PI*Freq*T)  ! Lloyd mirror eqn.
1030   Db(I,F)=10*LGT(A(I,F)*Det)
1040   NEXT F
1050  Avg1=Avg1*Angle(I)
1060  Avg2=Avg2+Angle(I)
1070  NEXT I
1080 Avg1=Avg1^(1/Nhyd)       !  Average angle computed as harmonic mean
1090 Avg2=Avg2/Nhyd           !  Average angle computed as ordinary mean
1100   FOR F=1 TO Fmax        !  Compute hydrophone data averages two ways
1110   Asum(F)=0
1120   Dbsum(F)=0
1130   FOR I=1 TO Nhyd
1140   Asum(F)=Asum(F)+A(I,F)*Det
1150   Dbsum(F)=Dbsum(F)+Db(I,F)
1160   NEXT I
1170   Asum(F)=10*LGT(Asum(F)/Nhyd)     !  Asum = AVERAGE OF POWER VALUES IN DB
1180   Dbsum(F)=Dbsum(F)/Nhyd           !  Dbsum = AVERAGE OF DB VALUES
1190   NEXT F
1200  DISP
1210  Plotdone=0
1220 Store:   !  STORE ASUM VALUES ON DISK WITH SUPPORT DATA
1230  BEEP
1240  Yesno=0
1250  INPUT "STORE COMPUTED VALUES ON DISK? (CONT=NO, 1=YES)",Yesno
1260  IF Yesno=0 THEN GOTO Print
1270  BEEP
1280  EDIT "ENTER MASS STORAGE UNIT SPECIFIER",Msus1$
1290  MASS STORAGE IS Msus1$
1300  BEEP
1310  INPUT "ENTER NEW FILE NAME",Name$
1320  S$=" "          !  CREATE SUPPORT DATA STRING
```

```
1330  FIXED 1
1340  Hl$=VAL$(Hyl)
1350  Wh$=VAL$(Wh)
1360  Sd$=VAL$(D1)
1370  Sw$=VAL$(Dx)
1380  Hr$=VAL$(Cpay)
1390  Hd1$=VAL$(D2(1))
1400  Hd2$=VAL$(D2(2))
1410  Hd3$=VAL$(D2(3))
1420  Hd4$=VAL$(D2(4))
1430  C$=Name$&S$&"HL="&Hl$&S$&"WH="&Wh$&S$&"SD="&Sd$&S$&"SW="&Sw$&S$&"HR="&Hr$
1440  C$=C$&S$&"HD="&Hd1$&S$&Hd2$&S$&Hd3$&S$&Hd4$
1450  PRINT C$
1460  FOR K=1 TO 34
1470  Xsum(K)=Asum(K)
1480  NEXT K
1490  CREATE Name$,1
1500  ASSIGN #1 TO Name$
1510  MAT PRINT #1;Xsum
1520  PRINT #1;C$
1530  ASSIGN #1 TO *
1540  PRINT "LLOYD-MIRROR DATA STORED IN FILE ";Name$
1550 Print:   ! - - - - - - - - - PRINT OUTPUT - - - - - - - - - - - - - - -
1560  BEEP
1570  Hc=0
1580  INPUT "PRINTED DATA FOLLOWS; WANT HARDCOPY?  (1=YES)",Hc
1590  IF Hc=1 THEN PRINTER IS 0
1600  PRINT "PROPAGATION ANOMALY VERSUS HYDROPHONE DEPTH AND FREQUENCY"
1610  PRINT
1620  PRINT "FROM FILE ";Name$
1630  PRINT
1640  IF L$<>"1" THEN PRINT "SQUARE LAW DETECTORS ASSUMED"
1650  IF L$="1" THEN PRINT "LINEAR DETECTORS ASSUMED"
1660  PRINT "VERTICAL LENGTH OF HYDROPHONE ELEMENT = ";Hyl;" INCHES"
1670  PRINT "OCEAN WAVE HEIGHT = ";Wh;" FEET"
1680  PRINT "MEAN SOURCE DEPTH = ";D1;" FEET"
1690  PRINT "SOURCE VERTICAL WIDTH = ";Dx;" FEET"
1700  PRINT "HORIZONTAL RANGE = ";Cpay;" YARDS"
1710  PRINT LIN(3)
1720  PRINT "HYDROPHONE DEPTH (FEET) AND ANGLE (DEG.)"
1730  IMAGE 12X,4(DDDD,4X),"PWR AVG.  DB AVG."
1740  PRINT USING 1730;D2(1),D2(2),D2(3),D2(4)
1750  IMAGE 13X,6(DD.D,4X)
1760  PRINT USING 1750;Angle(1),Angle(2),Angle(3),Angle(4),Avg1,Avg2
1770  PRINT "FREQUENCY"
1780  PRINT
1790  FOR F=1 TO 10
1800   IMAGE DDDDDD.D,3X,6(SDD.D,3X)
1810   PRINT USING 1800;Fre(F),Db(1,F),Db(2,F),Db(3,F),Db(4,F);Asum(F);Dbsum(F)
1820  NEXT F
1830  FOR F=11 TO Fmax
1840   IMAGE 2X,DDDDDD,3X,6(SDD.D,3X)
1850   PRINT USING 1840;Fre(F),Db(1,F),Db(2,F),Db(3,F),Db(4,F);Asum(F);Dbsum(F)
1860  NEXT F
1870  IF Hc=1 THEN PRINT PAGE
1880  PRINTER IS 16
1890  Yn=0
1900  BEEP
1910  INPUT "WANT PLOT?  (1=YES)",Yn
1920  IF Yn<>1 THEN GOTO Lastline
1930 Plt:   !   GENERAL DATA AND CURVE PLOTTING, CARTESIAN COORDINATES
1940  !     GRAPH SETUP DATA
1950  Ymin=-30
1960  Ymax=10
1970  Xmin=1
1980  Xmax=41
1990  Nvert=0
```

```
2000  Nhorz=40
2010  Xlabel$="FREQUENCY BAND, Hz"
2020  Ylabel$="ANOMALY, dB"
2030  Xsp=ABS(Xmax-Xmin)/Nhorz
2040  Ysp=ABS(Ymax-Ymin)/Nvert
2050  Ygap=ABS(Ymax-Ymin)*.005
2060 Plotgraph:        ! GENERAL GRAPH SETUP * * * * * * * * * * * * * * * * * *
2070  PRINT PAGE
2080  PLOTTER IS "GRAPHICS"
2090  GRAPHICS
2100  FRAME
2110  SETGU
2120  LOCATE 12,118,16,93    !    Defines graph area within 100 X 123 frame
2130  SETUU
2140  SCALE Xmin,Xmax,Ymin,Ymax
2150  LINE TYPE 3
2160  GRID 10,5,1,-30
2170  LINE TYPE 1
2180  AXES 1,5,Xmin,Ymin
2190  AXES 1,5,Xmax,Ymax
2200  !  LABEL GRAPH * * * * * * * * * * * * * * * * * * * * * * * * * * *
2210  DEG
2220  LDIR 90
2230  LORG 8
2240  CSIZE 2.4
2250  FOR I=1 TO 41                          !    Label x-axis numbers
2260  MOVE I,Ymin-Ygap
2270  LABEL Fre(I)
2280  NEXT I
2290  LDIR 0
2300  LORG 8
2310  FOR J=Ymin TO Ymax STEP Ysp            !    Label y-axis numbers
2320  MOVE Xmin,J
2330  LABEL J
2340  NEXT J
2350  SETGU
2360  CSIZE 3.3
2370  MOVE 65,2
2380  LORG 5
2390  LABEL Xlabel$                         !  Label x-axis title
2400  MOVE 3,50
2410  DEG
2420  LDIR 90
2430  LORG 4
2440  LABEL Ylabel$                         !  Label y-axis title
2450  LORG 1
2460  LDIR 0
2470  MOVE 110,1
2480  CSIZE 2.4
2490  LABEL "LLOYD"
2500  SETUU
2510  UNCLIP
2520 Plotdata: !   PLOTS DATA FROM UP TO 6 FILES USING 6 DIFFERENT SYMBOLS
2530  P$(1)="+"
2540  P$(2)="*"
2550  P$(3)="X"
2560  P$(4)="O"
2570  P$(5)="0"
2580  P$(6)="^"
2590  FOR I=1 TO Nhyd
2600  SETUU
2610  LORG 5
2620  CSIZE 2.4
2630  FOR J=1 TO Fmax
2640  X(J)=J
2650  Y(J)=Db(I,J)
```

```
2660  IF Y(J)>Ymax THEN Y(J)=Ymax
2670  IF Y(J)<Ymin THEN Y(J)=Ymin
2680  IF X(J)>Xmax THEN X(J)=Xmax
2690  IF X(J)<Xmin THEN X(J)=Xmin
2700  MOVE X(J),Y(J)
2710  LABEL P$(I)
2720  NEXT J
2730  SETGU
2740  MOVE 40+10*I,98
2750  LABEL P$(I)
2760  MOVE 40+10*I,95
2770  LABEL D2(I)
2780  NEXT I
2790 Finish:   !
2800  WAIT 4000
2810  BEEP
2820  Copy=0
2830  INPUT "WANT HARDCOPY? (1=YES)",Copy
2840  IF Copy=1 THEN DUMP GRAPHICS
2850  Plotdone=1
2860  PRINT PAGE
2870 Lastline:  !
2880  END
2890  !
2900  DEF FNDirect(Theta,Lambda,Hyd)
2910  !  HYDROPHONE VERTICAL DIRECTIVITY FUNCTION
2920  Arg=ABS(PI*Hyd*SIN(Theta)/Lambda)
2930  Direct=1
2940  IF Arg>0 THEN Direct=SIN(Arg)/Arg
2950  RETURN Direct
2960  FNEND
2970  END
```

REFERENCES

1. Fortuin, L., "Survey of Literature on Reflection and Scattering of Sound Waves at the Sea Surface," Journal of the Acoustical Society of America, Vol. 47, pp. 1209-1228 (1970).

2. Clay, C.S. and Medwin, H., "Dependence of Spatial and Temporal Correlation of Forward-Scattered Underwater Sound of the Surface Statistics," Journal of the Acoustical Society of America, Vol. 47, pp. 1412-1429 (1970).

3. Huang, J. C., "Analysis of Acoustic Wave Scattering by a Composite Rough Surface," Journal of the Acoustical Society of America, Vol. 49, pp. 1600-1608 (1971).

Note: An extensive survey of the literature on surface scattering as it may apply to ship acoustical trials was conducted by Applied Hydro-Acoustics Research, Inc. under contract to DTNSRDC in 1974. The survey was published in a final report No. TR 116. This survey included 72 reports and various related literature on the subject. This report includes some of the findings of that survey.